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Shading control strategy to avoid visual discomfort by using a low-cost camera: A field study of two cases

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ABSTRACT

Daylighting in offices creates a comfortable and healthy working environment for its users. However, maximizing the amount of daylight can cause visual hindrance. To improve the visual and thermal comfort for the users, designers implement shading systems, which control the transmitted solar and visual radiation. To ensure a comfortable indoor environment, designers need to choose an appropriate control strategy. Different control strategies exist, but the acceptance and satisfaction of the user regarding these strategies remains quite low. Therefore, we developed a control strategy that is based on the comfort requirements of the users. The control strategy aims at avoiding visual discomfort for the user, while optimizing for daylight availability and improving user satisfaction by providing the possibility to override the automated control of the shading system. This is the first study where a shading device is controlled by a controller system with a low-resolution camera. The controller system captures High Dynamic Range images and evaluates a visual comfort parameter, namely the 'Daylight Glare Probability'. The system controls the actuator of the shading device based on the assessed level of comfort. This paper demonstrates two experimental case studies where the controller system and the control strategy are implemented. The controller system is able to keep the visual hindrance below a predefined limit, while sufficient daylight can still enter the office room.

1. Introduction

Daylighting in offices creates a comfortable and healthy working environment for its users [1]. Additionally, daylighting has a positive impact on the global energy savings, because it decreases the energy consumption for artificial lighting [2]. Next to providing daylight, another important aspect for the user satisfaction is providing a view to the outside [3,4]. However, maximizing the amount of daylight may cause some issues. In particular, visual hindrance is the most negative side effect from windows. Also, excessive shortwave directly-transmitted solar radiation and longwave indirectly-transmitted energy can result in thermal discomfort and an increased energy demand for cooling. Thus, it is important to control the transmitted solar radiation to improve the visual and thermal comfort for the users. In Northern European climates, designers find it useful to implement shading systems, which can adapt themselves to changing weather conditions. Commonly used adaptable systems are adjustable in either horizontal or vertical direction (e.g. roller blinds, movable panels or venetian blinds). However, the overall performance to improve visual and thermal comfort, depends on their control strategy.

Different shading control strategies exist to achieve a comfortable indoor climate. A widely accepted control strategy for venetian blinds is tilting the slats to their time-dependent cut-off angle. As a result, the slats block the direct incident solar radiation and they allow diffuse light to enter the office space [5–7]. In this case, an outside view for the user is largely preserved. Other control algorithms use control parameters to adjust the shading system. As an example, Thalfeldt and Kurnitski [8] simulate different control algorithms based on their impact on the energy performance and duration of unobstructed view. They propose to use the horizontal illuminance on the working plane as a control parameter during working hours and the temperature of the room as a control parameter for shading control outside working hours. Another study, of Gunay and O'Brien [9], uses the ceiling illuminance as a control parameter to open the indoor roller blinds and to turn off

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the artificial lighting when sufficient task lighting is provided. This strategy reduces the electricity demand for artificial lighting up to 25%. Although the aforementioned strategies control the transmission of solar radiation, researchers evaluate their performance merely by checking the impact on the energy need, without considering the visual comfort of the user. Karlsen, Heiselberg and Bryn [10] use questionnaires to explore the user satisfaction. The users indicate the preserved outside view as an advantage of the cut-off angle strategy, but as a disadvantage, users indicate that using the cut-off angles is not always sufficient to avoid glare. The cut-off angle strategy can cause glare by a specular reflection of light on the slats of the venetian blind.

The choice of an appropriate control strategy, which avoids visual discomfort, is crucial for user acceptance and satisfaction. Furthermore, users prefer a user-controllable indoor climate and, in general, they do not accept a fully automated control strategy. The choice of manually controlled shading strategies improves the user's visual comfort and satisfaction. However, the fully manual controlled shading systems are more often closed than required. This results in lowered thermal and visual comfort and in an increased energy demand for artificial lighting [11,12]. To overcome the issues in fully automated or fully manual controlled shading strategies, designers can give the user the possibility to override the automated control. Different studies, using different control parameters and strategies exist.

In this section, some examples and recommendations are given on these manual override actions and the resulting user satisfaction. Next, some examples are given which can improve the user acceptance by using an adaptive user-learning control strategy and by providing feedback. A field study of Meerbeek et al. [13] investigates how office workers react to an automated control of venetian blinds with the possibility for manual override and the option to turn off the automated control. The results show that a large majority of the users choose to turn off the automated mode. The study concludes that the perceived level of control influences the visual comfort assessment of the users. A study of Reinhart and Voss [14] shows that using only vertical illuminance as a control parameter for an automated venetian blind control strategy leads to low user acceptance. As in this case, 88% of the automated control actions are overridden by users. Bakker et al. [15] also investigate in a field study the influence of an automated control strategy on the user satisfaction. This study uses varying control strategies where the position of the roller blinds is pre-determined or controlled by vertical illuminance. Each of the scenarios is tested with and without a manual override option. The results reveal that a manual override of the automated roller blinds leads to a higher user satisfaction regarding the illuminance levels in the interior environment and the view out. In addition to these results, an implementation of an adaptive-learning strategy can improve the user satisfaction even more. The results of Gunay and O'Brien [16] show a decrease of 80% in the override actions by the users when using an adaptive user-learning control strategy. Their study demonstrates in a numerical simulation context the preferences of a user regarding manual control, automated control with fixed set-point for illuminance and adaptive user-learning control of the venetian blinds. Furthermore, another study shows that making the user aware why a certain control is implemented also increases the user satisfaction. Namely, Meerbeek et al. [17] use a gradual light feedback system to communicate the intentions of the automated venetian blinds to the users. This reduced the amount of override actions by the user from 50,8% to only 3,6%.

It is clear that the possibility of a manual override of an automated control strategy leads to higher user acceptance and satisfaction, but the chosen control strategy and control parameter influence the amount of override actions. A promising and robust parameter for evaluating visual comfort related to daylight [18,19] is the ‘Daylight Glare Probability’ (DGP) parameter. This parameter has a good correlation to what a person actually perceives [20]. Other glare parameters are mostly suitable for artificial lighting or indirect sunlight [21].

Hence, we need an appropriate control strategy that avoids visual discomfort, while minimizing the number of override actions by the user through an adaptive user-learning algorithm, and while optimizing the daylight availability on a working plane to ensure a comfortable and healthy working environment. Instead of using multiple sensors for daylighting, and shading control and sensing the presence of a user, there is a potential to use a camera as a replacement of these multiple sensors [22]. Therefore, we developed a control strategy, based on the ‘Daylight Glare Probability’ as a visual comfort parameter. We used a small, low-cost, and multifunctional single-board computer, namely a Raspberry Pi, with an attached low-resolution camera as a controller system. This controller system is developed by the authors at the architectural engineering research lab of the VUB, during the European project Smartblind (PF7 314454) [23]. First, the controller system evaluates the visual comfort in the interior environment, by taking pictures and evaluating them. Second, based on the results of the assessment, the controller algorithm decides whether the position of the shading system should be changed or not. Each time-step the controller system sends a control signal to the actuator of the shading device [24]. A user can override the automated control and at this point the controller algorithm adapts itself to the preference of the user. The adaptive response of the controller system helps to anticipate and minimize the number of override actions.

The goal of this research is to develop an improved control strategy which can optimize visual comfort and at the same time reduce the energy consumption for heating, cooling and the electricity use for artificial lighting. By using the DGP as a control parameter of a shading device, we can improve the visual comfort for the user and by allowing a manual override, we increase the user acceptance and satisfaction. This paper demonstrates the performance of the control strategy and validates the low-cost controller system through in-situ measurements in two case studies. The first case study consists of a mock-up office cell with a venetian blind as a shading device. The tests were performed with and without the presence of a user. The second case study consists of a real office environment, namely an open-plan office space with 56 users and adaptable external roller blinds.

2. Procedure and measurements

2.1. Glare metrics

The DGP parameter is used to assess the visual comfort. The software tools Radiance [25] and Evalglare [26] are used to evaluate glare for each luminance map. An illuminance sensor measures the vertical illuminance at the position of the camera and this value is inserted into Evalglare, to ensure an accurate calculation of the DGP. Glare sources are identified as the areas where the luminance exceeds 5 times the average luminance in the image. The value of 5 is defined as the optimal setting [21]. The DGP value depends on the view direction and the position of the viewer in the room and is calculated by (1)

$$DGP = 5.87 \cdot 10^{-5} \cdot E_v + 9.18 \cdot 10^{-2} \cdot \log\left(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right) + 0.16 \qquad (1)$$

where E_v [lux] is the vertical illuminance, L_s [cd/m^2] is the luminance of the glare source, ω_s is the solid angle of the glare source and P is a position index. According to the DGP scale, glare becomes perceptible when it exceeds a value of 0,35. It becomes disturbing when a value of 0,40 is exceeded and a higher value than 0,50 is intolerable.

2.2. Using a low-resolution camera

The proposed control strategy uses a camera as a picture sensor. The authors demonstrate the possibility to use a small low-cost and low-resolution (5 megapixel) camera. The camera has a OV5647 image sensor with a resolution of 2592x1944 pixels and an image sensor area of 3,76 mm x 2,74 mm. It has an output format of 8-/10-bit RAW RGB data. The camera has a low-cost Waveshare (6 mm F2) fisheye lens attached to it that captures 157° horizontally and 139° vertically.

To validate this method, we compared the measurement results of this low-resolution camera to an approach using a more expensive and higher resolution camera (24,1 megapixel). The high-resolution camera consists of a Nikon D5200 DSLR camera. It has an image size of 6000 x 4000 pixels and an image sensor area of 23,5 mm x 15,6 mm. The camera has an output format of 14-bit RAW data. A fisheye lens is attached to both cameras, so they can assess a large field of vision. A Sigma (4,5 mm F2,8 DC circular) fisheye lens, that captures 180° horizontally and vertically, is attached to the Nikon camera. The range of luminance values that are measured with the high-resolution and low-resolution camera is 0–500.000 cd/m^2 and 0–13.200 cd/m^2, respectively (Fig. 1). The range of the latter is significantly lower than the first, although it is sufficient for this purpose, as the difference in luminance between a clouded sky, intermediate sky and clear sky (with or without sun) can still be detected.

Both cameras went through a calibration procedure. The software Pfstools [27] was used to determine the response curve of the each camera. The response curve gives the relation between every pixel and the intensity of light. The camera takes several pictures with each a different exposure time in order to capture the low-lit and over-illuminated details in the scene. All these images are merged into one High Dynamic Range (HDR) image, i.e. an image that has a broad range of luminance values [28]. Relative values of luminance can be read from the merged HDR image. By using a point luminance meter and a luminance camera, the HDR images can be scaled to measure, instead of relative luminance values, absolute luminance values. Consequently, the HDR image is more representative to what a human eye perceives than a regular single image. Therefore, these images can be used to measure the luminance distribution in the room and they can help to evaluate visual comfort as a user would perceive it.

Afterwards, the high-resolution camera is corrected for vignetting, using the Mirrorbox at the Belgian Building Research

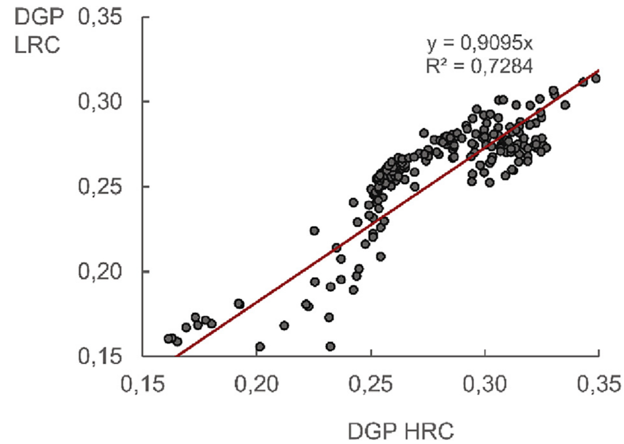

Fig. 2. The comparison of the calculated DGP value of the calibrated high-resolution camera (HRC) and the low-resolution camera (LRC) shows that the DGP of the LRC is underestimated.

Institute [29]. The images of the high-resolution camera are transformed from an equisolid projection to an equidistant projection, in order to be compatible with the Evalglare software. The next step is to compare both cameras on their evaluation of the DGP value. The values are compared in a range of 0,15 to 0,35, which is the most common range of obtained DGP values. The comparison was made for the same view as shown in Fig. 1. The sky conditions varied from an overcast sky, to a rapidly changing intermediate sky, and to a sunny sky condition with and without a user present. The sunny sky condition consisted of periods with a lowered venetian blind. In general, the calculated value of the DGP was higher for the fully calibrated high-resolution camera, than for the low-resolution camera (Fig. 2). The lower the DGP value, the more the values significantly differ. Thus, the low-resolution camera has more difficulties to detect small glare sources. These results give an indication that the low-resolution camera could underestimate the glare sources by 9% as an average.

2.3. Case study 1

2.3.1. Experimental set-up

The measurements were conducted at the Vrije Universiteit Brussel (VUB) in Belgium. The VUB is located in the southeast of Brussels (Etterbeek, 50°49′ N 4°23′ E). The set-up consists of a mock-up office room and has a dimension of 2,4 m × 3 m x 2,4 m (HxLxW). The room is located on the fourth floor of a building on the university campus. The room has one window (1,25 m x 0,9 m) with a southwest orientation and interior venetian blind shading system, positioned at the interior. A table is positioned in front of

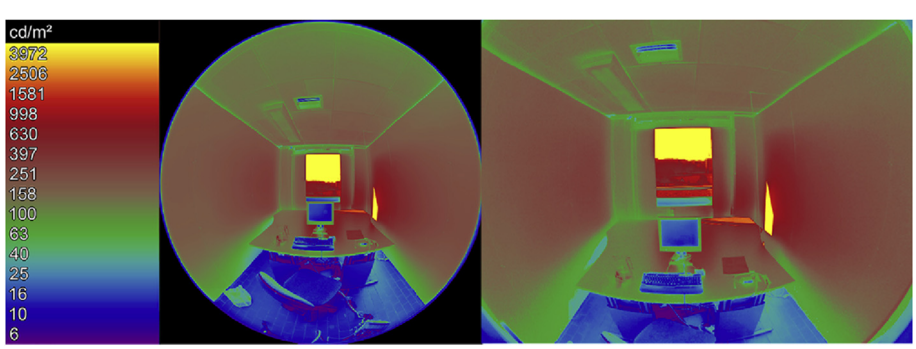

Fig. 1. The difference between a luminance map of the high-resolution camera (left) and the low-resolution camera (right).

the window with a chair for a potential user at 2 m from the window. The controller system is positioned, together with the high-resolution camera, at 2,4 m from the window and at a height of 1,4 m (Fig. 3).

2.3.2. Equipment

As a shading device, a Griesser Lamisol venetian blind system was chosen because of its large adaptability: the slats can be tilted from 0 to 90° in a deployed state. Due to this large adaptability, the transmitted solar radiation can be precisely controlled. The slats have a width of 96 mm and a spacing between the slats of 92 mm. The blind has a grey colour. A high accuracy illuminance sensor (Hagner Digital Luxmeter (model E4-X)) measures the vertical illuminance at the height of the controller system, together with a BH1750FVI digital light sensor module Gy-30, which is a miniature illuminance sensor and which is connected to the controller system. Another miniature illuminance sensor is positioned on the table to measure the horizontal illuminance. In order to measure the luminance distribution in the room, the high-resolution camera and the controller system with the attached low-resolution camera were installed. Both cameras have their line of sight directed to the window. A Quadra weather station is installed on the roof, to monitor the solar irradiation. A KNX system is used to actuate the shading device. All the equipment is connected to the same network, so that all data is accessible within this network. No artificial lighting was used during this experimental set-up.

2.3.3. Scenarios

2.3.3.1. Scenario 1. During several months the controller system with the attached low-resolution camera has been tested in comparison to the high-resolution camera. In this case the venetian blinds are automatically controlled by the controller system. No participants were present in the room. The controller assesses visual comfort and decides whether the shading system should be actuated. The low-resolution camera takes pictures with a time-step of 2 min. Every 2 min a new HDR image is created and the image is evaluated to determine the DGP value. If the amount of glare exceeds the predefined limit, then the controller system sends a signal to the actuator of the shading device. The venetian blinds are first lowered with a horizontal slat position. Based on the evaluated visual comfort, the slats can be rotated each time-step with a 10° step. Once the blinds are put down, they remain down for at least 20 min, in order to avoid blinds moving up and down during rapidly changing weather conditions. Too much movement of the blinds could cause disturbance for the potential users. On the other hand, the control algorithm shouldn't supercharge the motor of the venetian blind. Each motor has a limited number of cycles of retraction, extension or tilting, which are defined by classes of endurance (EN 13561). The middle class (class 2) corresponds to a 10 years use with two cycles per day.

2.3.3.2. Scenario 2. For the second scenario, the same automatic control strategy is applied, but a user is also present in the room. Each participant worked in the office room during one afternoon.

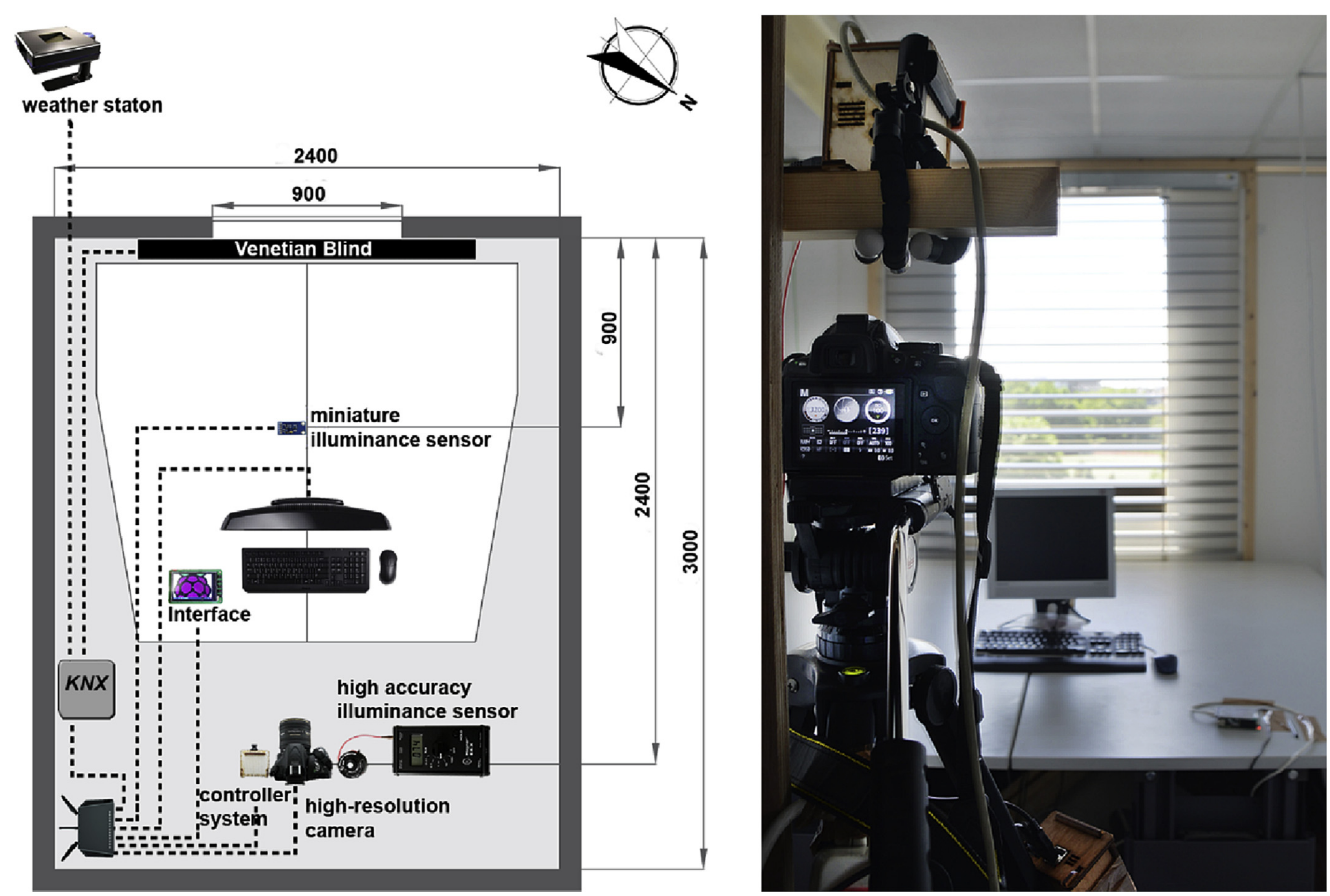

Fig. 3. Plan view of mock-up office room (left) and the position of the high-resolution camera, the controller system and the illuminance sensors in the office room (right). All dimensions are shown in millimetres.

The participants had access to a graphical user interface, so that they could override the automatically controlled venetian blind according to their preferences. The user interface distinguishes between the general amount of light in the room, indicated as ‘illuminance’, and the perceived visual hindrance, indicated as ‘glare’. The interface consists of a small touch-screen panel and has got three buttons to change the blind settings: one to lower the amount of glare, one to lower the illuminance level and one to increase the illuminance level. If the user overrides the automated control, then the predefined set-point for the DGP in the control algorithm is changed, according to the preferences of the user.

2.3.3.3. Scenario 3. As a visual comfort parameter, the DGP has a good performance to estimate the glare a person perceives. However, using the DGP as a sole metric to control visual comfort in a scene, does not seem to be sufficient, as sometimes glare sources can be underestimated [30]. Therefore, the authors chose to implement another control strategy, which combines the cut-off angle control strategy and the strategy used in the first scenario. Using the cut-off angle will avoid direct solar radiation to enter the room. The cut-off strategy is implemented as soon as the irradiance on the façade attains a value of 150 W/m^2 or higher. The set-point for irradiance was chosen based on previous studies [10,31]. Hence, at this point only diffuse light will enter the room. Additionally, when using an external solar shading device, the thermal comfort would be increased as well. However, as mentioned previously, the cut-off strategy is insufficient to avoid visual discomfort. Therefore, the visual comfort remains assessed as well, using the strategy from scenario 1. The cut-off angle was calculated using the formula proposed by O'Neill [32]. First the profile angle (d) (2) is calculated from the solar altitude (α) and the solar azimuth (γ), these data are provided by the weather station every minute.

$$d = \tan^{-1}\left(\tan(\alpha)/\cos(\gamma)\right) \tag{2}$$

Second, the cut-off angle ($\beta_{cut\text{-}off}$) can be calculated (3), using the profile angle (d) and the spacing between the slats (s) and the width of the slats (w).

$$\beta_{cut-off} = \sin^{-1}(\cos(d)*s/w) - d \tag{3}$$

2.3.4. Participants

In total, 5 people participated in the experiment (1 male, 4 females, aged between 24 and 33 years). The participants were each asked to perform their regular work in the mock-up office room during one afternoon (3–4 h). The desktop computer was available for the users to work on, although almost all used their own laptop. All the experiments with users were performed on a day with a sunny or, at least, an intermediate sunny sky.

2.4. Case study 2

2.4.1. Experimental set-up

The measurements were conducted in an office space of the firm Renson in Waregem (50°51′ N 4°25′ E), Belgium. The set-up consists of a landscaped office room and has a dimension of 4 m × 36 m x 14 m (HxLxW). The room has got three separate roof lights, one large roof light on the south-east side of the ceiling and the north-west side walls are also almost fully glazed (see Fig. 4). There are 56 users working in this office area.

2.4.2. Equipment

On the roof lights, there are 12 external fabric roller blinds positioned, they have a visual and solar transmittance of 20% with a white colour and a Soltis polyester fabric. The roller blinds are automated in pairs, so 6 separate parts can be actuated (Fig. 4). The blinds can be raised or lowered over a sloped glass surface to an intermediate state or to a closed position. On the side windows, external glass fibre roller blinds (sergé weaving type) with a visual and solar transmittance of 3,6% and a dark grey colour are used. There is a Somfy weather station positioned on the roof, which measures the outside illuminance. A Gira illuminance sensor is positioned on one of the internal beams. The controller system is positioned on a cabinet with the view direction to the South-West. A KNX system is used to actuate all the roller blinds. All the data from the blinds, the weather station, the illuminance sensor and the controller system is logged on the same network and thus accessible within this network.

2.4.3. Scenario

The experimental measurements focus on the upper roller blinds that are attached to the roof lights, because these roller blinds have the largest influence on the visual comfort in the interior environment of this office space. Almost no direct sunlight enters the room through the side windows, because of the presence of an adjacent building. There is a controller system positioned in the room that evaluates the visual comfort in the interior space. Based on the evaluated visual comfort, the controller system controls blind number 3 (Fig. 4). However, the users are still allowed to manually override this blind. In order to make a comparison between the difference in actuation results of an automated blind and a manually controlled blind, the other blinds are uncontrolled. All the other roller blinds are thus operated manually by the users.

The controller system takes pictures every 5 min and each time creates a new HDR image to determine the DGP Value. If the amount of glare exceeds the predefined limit, then the controller system sends a signal to the actuator of the roller blinds. The blind is first lowered completely. If the amount of glare becomes acceptable, the blind will open itself in steps of 25%. The amount of glare is evaluated at each time-step of 5 min. Each intermediate opening position is maintained for at least 10 min before the position of the blinds is changed, in order to avoid disturbance by the blinds. Once the blinds are completely closed, they remain closed for at least 20 min.

2.4.4. Questionnaire

Based on previous surveys [20,33], the authors made a questionnaire. The goal of this questionnaire is to check what the user perceives. During one month, the users of the room were asked to fill in a questionnaire each time they wanted to operate one of the blinds (Fig. 5). All data of the position of the blinds was logged on the KNX system, which made it possible to check whether the questionnaire was indeed filled in as asked. The questionnaire consists of two parts: some personal questions and some questions about the control of the blinds. The users also indicated on a plan their position in the office room.

2.4.5. Participants

There are 56 users in the room, 29 filled in their questionnaire, so 25 males and 4 females participated in the experiment. The users had a varying presence in the room from 8 o'clock until 19 o'clock. The age of the users varied from 25 to 65.

3. Results and discussion

3.1. Case study 1

3.1.1. Scenario 1

The first scenario shows a sunny day in March (25/03/2017) where the venetian blinds are controlled automatically by the

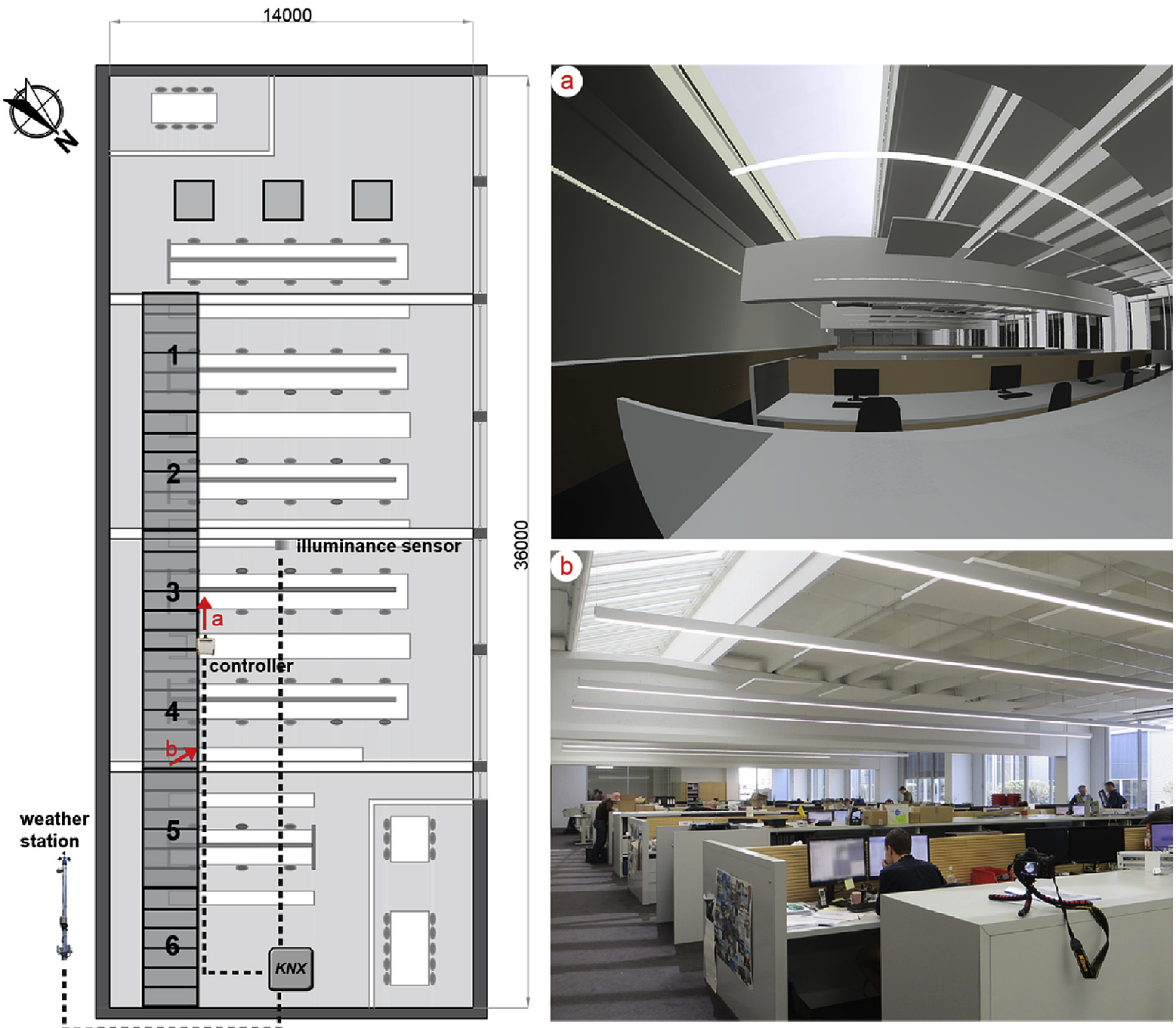

Fig. 4. Plan view of the open office space (left) with the indicated position of the illuminance sensor, the controller system, the blinds (1–6) and the weather station. Two images (right) show the view direction of the controller system (a) and another position in the room (b).

controller system (Fig. 6). Every 2 min several pictures are taken with the low-resolution camera to create a luminance map from a HDR image. At 14h02 the controller system sends a signal to the actuator of the venetian blind to lower it with a horizontal slat, because the amount of glare exceeds the predefined limit of 0,32 for the DGP. A limit of 0,32 is used, to avoid that the perceptible glare limit of 0,35 would be reached. At this point the sun is shining directly on the table. At the second action, the blind angle is changed from 0 to 10°, but still, there is some direct light on the table. At certain times, the direct sunlight is shining through the slats on the illuminance sensor on the table, which captures values up to 17klux. From 15h05, the sun is in the field of view of the controller system and not only the direct light on the table is causing an issue, but also the reflections on the slats, as can be seen on the luminance maps. Before noon a mean vertical illuminance of 380 lux is measured at the position of the controller system and camera. At 17h53 the blinds start to open again in steps of 10° and finally the venetian blind is retracted.

According to the European standard on lighting (EN 12464-1) a minimal illuminance on the task area of 500 lux is required for writing, typing and reading. In the immediate surrounding area a value of 300 lux is required. The average vertical illuminance, before (12h30 until 13h57) and during (13h58 until 18h21) the time that the shading system was deployed, was 1263 lux and 1221 lux respectively. The average horizontal illuminance in the room before and after the deployment of the venetian blind was 1906 lux and 2691 lux, respectively. At certain time-steps the sun was shining directly on the table, which gave high peaks in the measurements of horizontal illuminance on the table. An average horizontal illuminance of 1455 lux is measured, when the instantaneous peaks in high illuminance are filtered out. The results show that the minimal amount of illuminance is largely achieved. The results also show that an acceptable DGP value of 0,32 or lower can be attained, even if the horizontal illuminance is much higher (up to 1500 lux) than the required minimal value of 500 lux. Thus, sufficient daylight was available using this control strategy. Furthermore, the advantage of

1. Personal questions

Gender			
☐ M	☐ F		
Do you wear glasses?			
☐ Reading	☐ Driving	☐ Always	☐ Never
What is your age?			
☐ <30	☐ <40	☐ <50	☐ <65

2.Control of screens

date …./…./….	time … h … min	screen number …
You altered the position of a screen because you would like…		
☐ more light in the interior environment	☐ less light in the interior environment	☐ less glare
☐ more light on the computer monitor	☐ less light on the computer monitor	☐ to open a window
☐ more light on the table	☐ less light on the table	
Indicate the amount of glare		
☐ imperceptible	☐ disturbing	
☐ perceptible	☐ intolerable	

Fig. 5. Questionnaire that was filled in by the users each time they changed the position of the blinds.

using venetian blinds as a shading device offers the possibility to look outside while visual comfort is maintained. However, there were some possible glaring reflections that remained unnoticed by the low-resolution camera.

3.1.2. *Scenario 2*

During the second scenario, a user is present in the room and he or she is given the possibility to override the actions of the controller system. The tests were performed on different days in February and March. The weather conditions varied from a sunny (user 4 and user 5) to rapidly changing sky conditions (user 3) and to an intermediate sky (user 1 and 2) (Fig. 7).

The overview of the actions by the user and the controller system (Fig. 8) shows that for a higher vertical illuminance than 600 lux at the position of the controller system, the resulting actions are almost all closing actions, while the DGP varies between 0,22 and 0,34. Hence, this confirms that the vertical illuminance is an important parameter to assess visual comfort. For a DGP between 0,22 and 0,34 the values for the global outside illuminance vary between 10 klux and 80 klux, thus, the interior comfort conditions and illuminance levels are dependent on the state of the venetian blinds. Therefore, a control strategy solely based on outdoor conditions, e.g. the solar irradiance, cannot guarantee that the visual comfort is optimized in the office room. An average daylight factor (DF) is calculated (4) using the outdoor global illuminance (E_o) and the indoor horizontal work plane illuminance (E_i) for the points given in Fig. 8. The daylight factor equals 2,6%.

$$DF = E_i / E_o \cdot 100 \quad (4)$$

For the second scenario, an overview of the results of the measurements with user 4 are shown, the weather conditions were sunny and the user was fairly interactive. The measurement took place in March (16/03/2017). The venetian blinds were controlled automatically by the controller system. However, the user overrides the controller system three times (Fig. 9). The user was asked to let her eyes adapt for 5 min when she entered the room, afterwards, she was allowed to change the position of the blinds, which she immediately did because the room was too bright for her. This lead to an alteration in the DGP set-point of the controller system, according to the wishes of this user. After two actions of the user, the controller system changed the state of the venetian blind for the following three actions. The third action was induced because a glaring reflection appeared on the slats and some direct sunlight shined through the slats onto the table, due to the fact that the sun appeared in the field of view. After some time, the user altered the position of the blind, because of direct sunlight on the table and glaring specular reflections on the slats. Thus, this resulted in a lowered set-point. Afterwards, the controller system detected the direct light on the table and closed the slats more, to an angle of 60°. The average illuminance on the table during this afternoon was 1344 lux and an average vertical illuminance of 1219 lux was measured at the position of the controller system. This indicates that there was a uniform illuminance distribution in the room and the control strategy still allowed an availability of daylight of more than the minimal required value of 500 lux.

3.1.3. *Scenario 3*

A day in the beginning of April (13/04/17) is highlighted for the third scenario (Fig. 10). No user was present in the room. As shown previously, the DGP can underestimate the amount of glare when direct sunlight is present in the scene. The authors want to improve the control strategy by not only controlling on the DGP, but also on the cut-off angle. The data from the weather station is logged by the KNX network and thus accessible for the controller system. The cut-off angle is calculated and the controller system monitors the amount of solar radiation on the South façade. After 15 h, the position of the sun is in the field of view of the camera, which results in a higher amount of glare and thus in the shading system being operated. After the second action, the direct sunlight on the table is avoided, however some reflections on the slats of the shading system remain visible. These reflections on the slats cause an

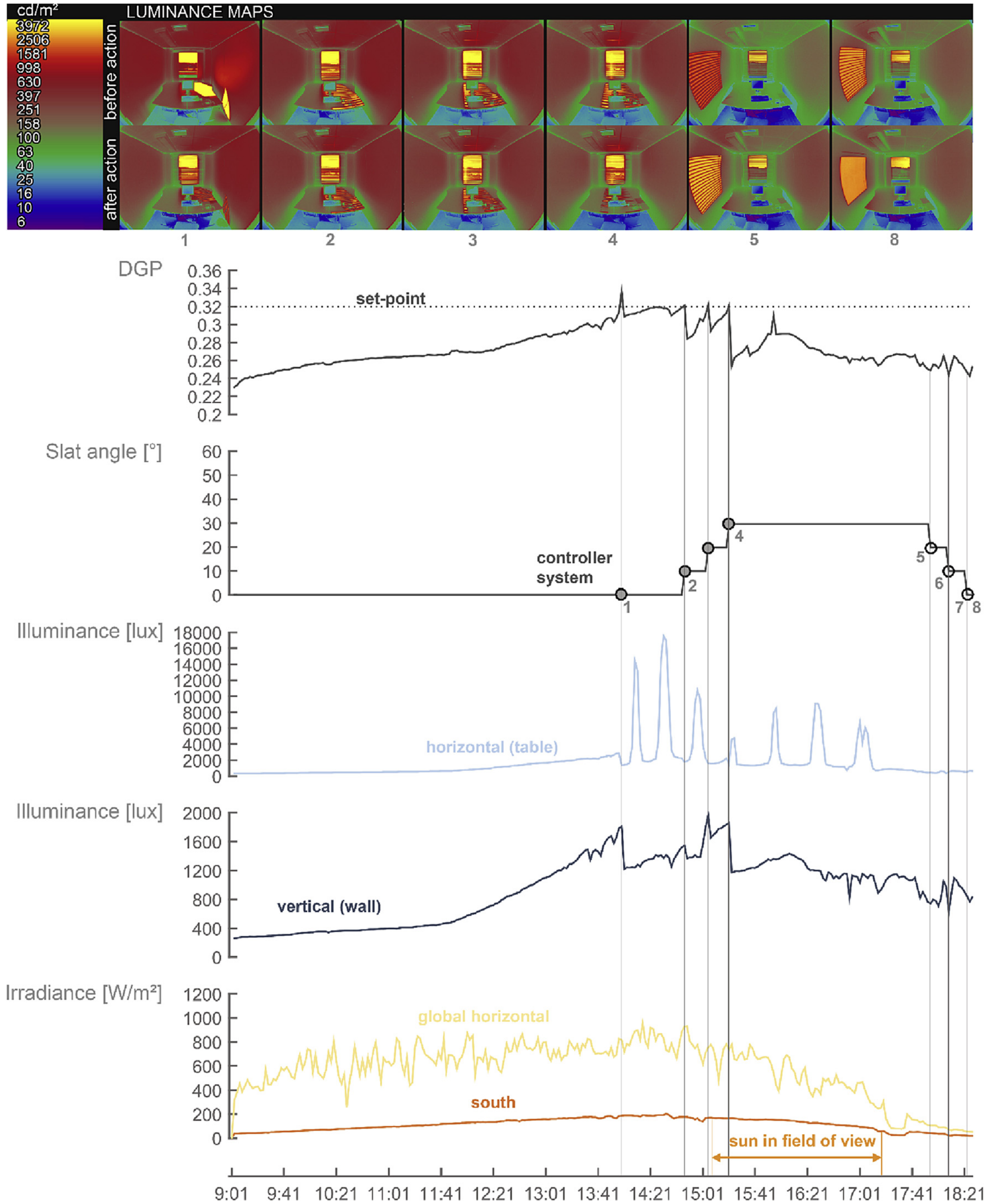

Fig. 6. The luminance maps before and after an action show how the position of the venetian blind is altered according to the predefined set-point for a sunny day in March.

increased value for the DGP and vertical illuminance at the position of the camera. Only a few minutes later, the controller system closes the slats a bit further, which removes the reflections and reduces the DGP and vertical illuminance. The weather is changing constantly and shifting back and forth from a sunny to a cloudy sky. At 16h03 the direct irradiance on the South reaches a value of 150 W/m^2 and thus the controller system implements the cut-off strategy and positions the slats at an angle of 34°, to keep the direct sun out of the room, but at the same time letting the diffuse sunlight enter the room. Before this action took place, the DGP value remained below the set-point, however there were some glaring reflections on the slats. Consequently, the cut-off strategy enhances the visual comfort. Implementing this cut-off strategy using an external shading system, would also help to improve the thermal comfort for the users and reduce cooling needs. From 17h53 on the global outside irradiance drops, as well as the DGP and the slats are opened again. The average vertical illuminance in the afternoon, before and after the shading system was deployed, equals 731 lux and 707 lux, respectively. As during the whole afternoon the weather fluctuates quite similarly, this indicates that, even though the shading system was in use, the illuminance level is not reduced a lot, maintaining a sufficient amount of daylight in the

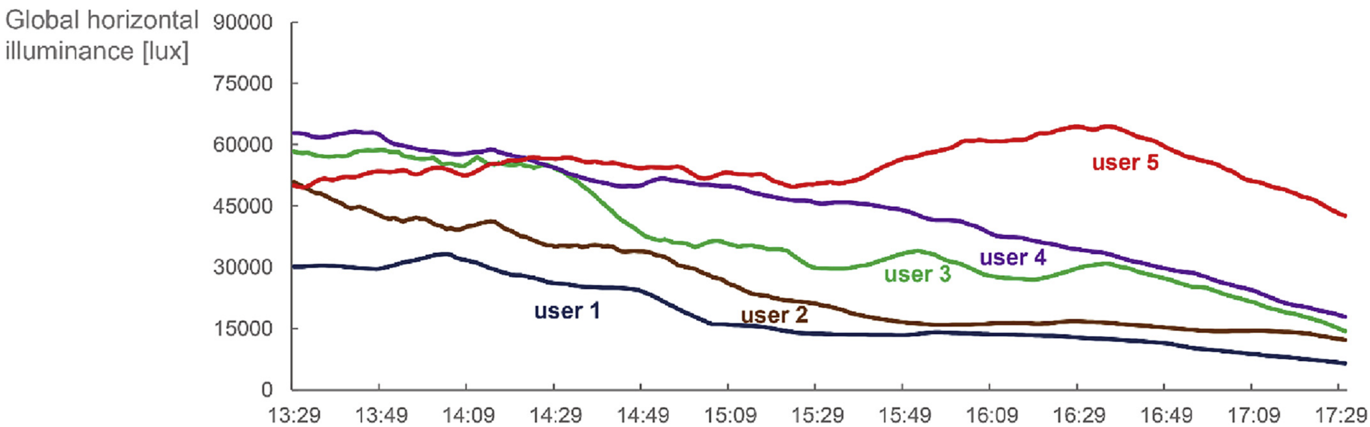

Fig. 7. A running mean graph of the global horizontal illuminance outside during the different measurements with the users shows the varying weather conditions during the test.

room. The average horizontal illuminance on the table in the afternoon, before and after the shading system was deployed, equals 2711 lux and 1503 lux, respectively. Before the shading system was deployed, the illuminance sensor on the table measured peaks as the direct sunlight on the table was varying due to the weather conditions. After the shading system was deployed, the horizontal illuminance dropped, but remained above the minimal required illuminance level of 500 lux.

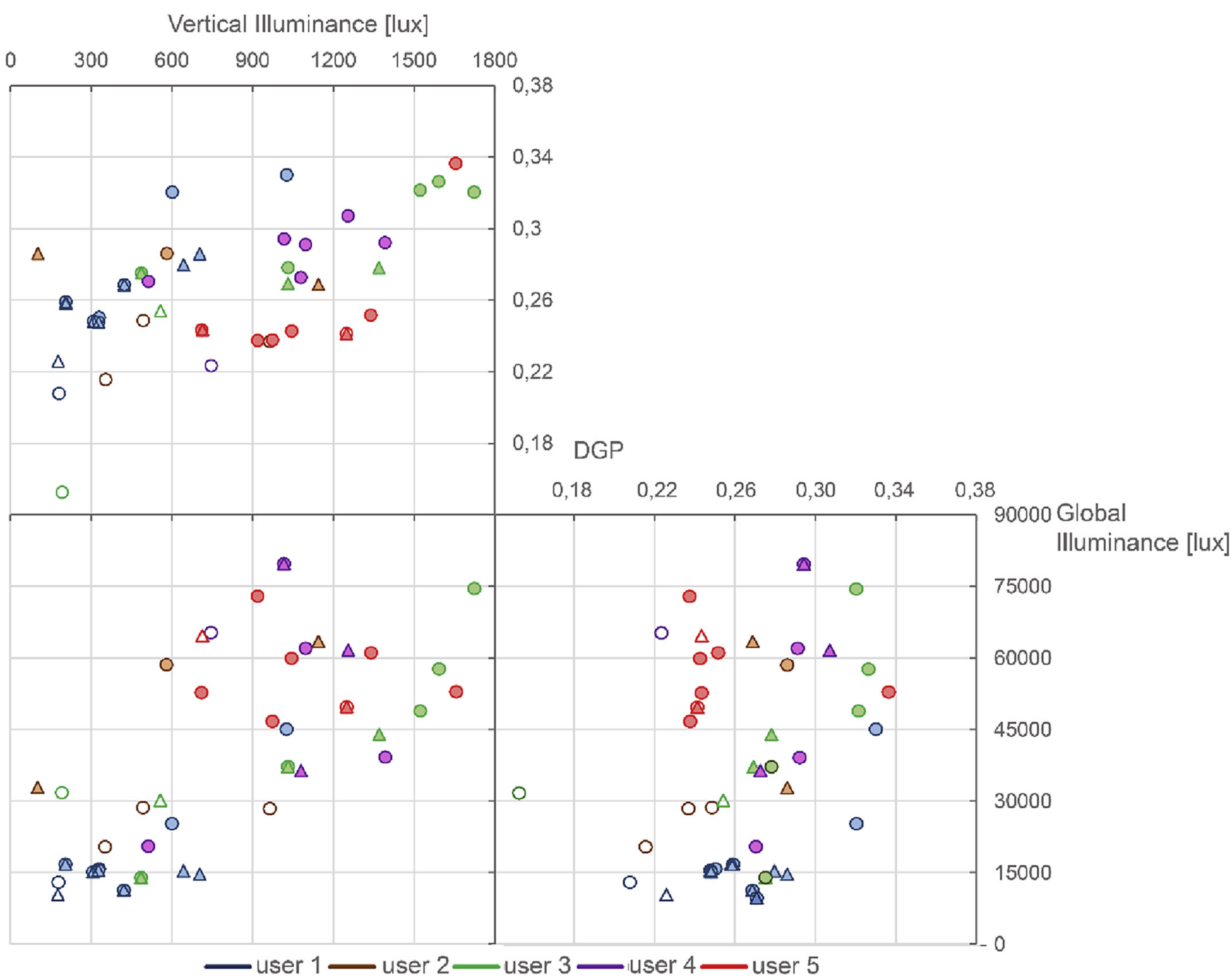

Fig. 8. Overview of the actions of the controller system (circle) or user (triangle) to put the shading system in a more closed (filled) or more open (not filled) position. The values of the DGP, vertical illuminance and global illuminance are shown on the time of the action, thus before any change to the state of the shading system occurs.

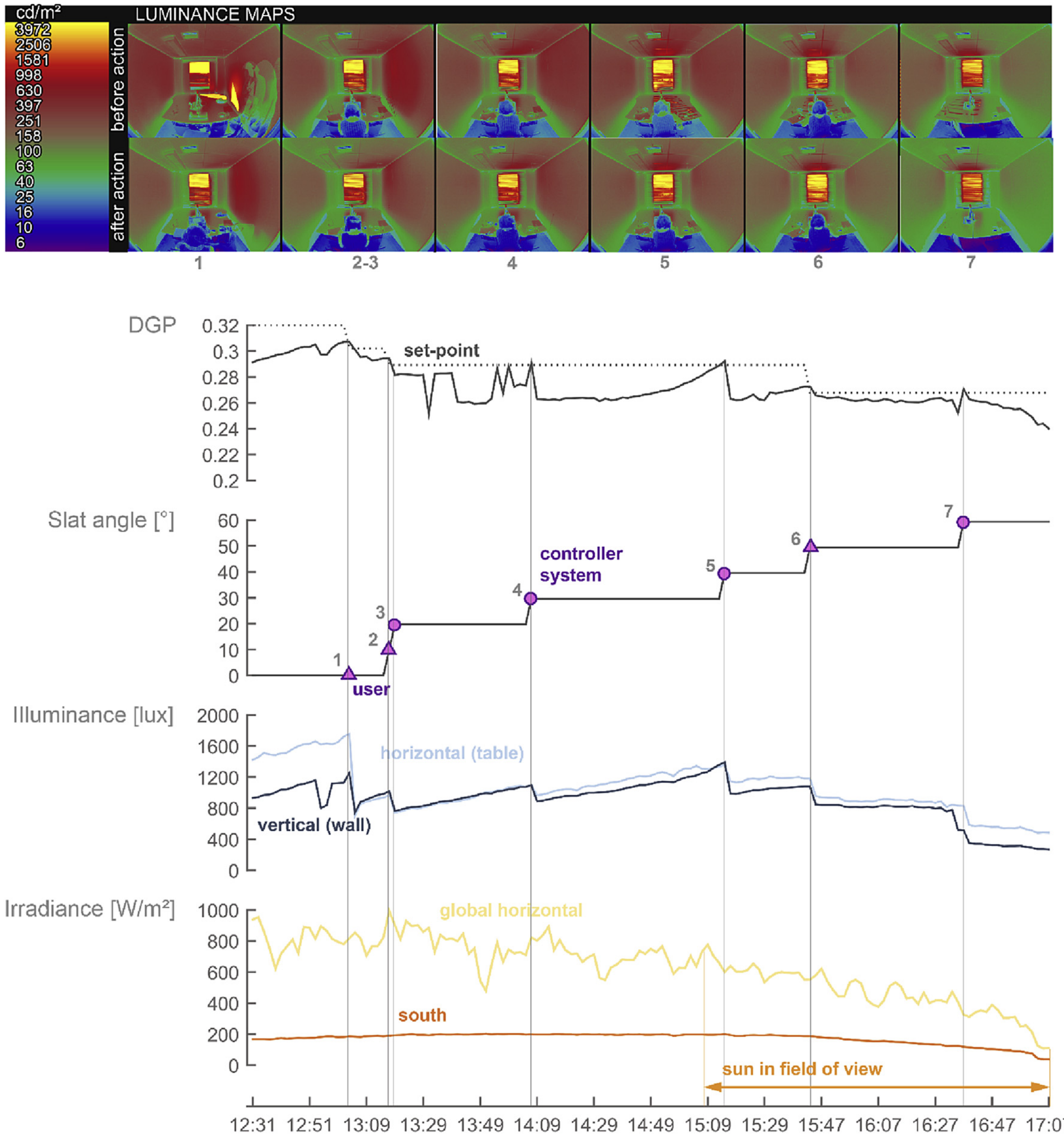

Fig. 9. The user manually overrides the control of the controller system, which results in an adaptation of the set-point.

3.2. Case study 2

The measurements were conducted in October 2016. All data was compared for working days only, when people were present. From the 6 upper roller blinds in the room, only blind 1 to 4 were actively used. The people seated under blind 5, did not fill in the questionnaire and there are no desks located under blind 6 (Fig. 11). Thus blind 1 to 4 were the focus of this study. All the people seated under blind 2 filled in the questionnaire and also 50% of the people seated at the desks under blind 3, blind 1 and blind 4 filled it in. In total, 29 people filled in their questionnaire. The questionnaire showed that there were 11 different people that operated the blinds and 18 others that filled in the document, but did not operate the blinds. Due to the low position of the sun in October, direct sunlight is able to enter the room quite far. According to the questionnaire results, only the users sitting at the far end of each row of desks (zone 2 in Fig. 11) never complained about visual hindrance. The users in zone 1 (orange zone in Fig. 11) did experience visual discomfort due to the roof lights. There was no significant difference between the amount of closing and opening actions for blind 1, 2 and 4 (Table 1). In total, the users changed the status of all the roller blinds 55 times and 27% of the time the questionnaire was not filled in. Blind 3 was automatically controlled by the controller system, but a manual override by the user was possible. The controller system changed the position of this blind 252 times, to close the blind completely or to any intermediate state (Table 1). 66% of the actions of the controller system opened the blind to an intermediate state or to a fully open position.

The users overrode the actions of the controller system (blind 3) 12 times, from which 11 times to open the roller blind, to have more light in the interior environment as derived from the questionnaire. The set-point for glare was set more stringent in this case study, to a DGP value 0,30 instead of 0,32, in order to avoid visual hindrance by an underestimation of the glare sources. As a result, only one action was performed to close blind 3, due to visual hindrance.

The questionnaire showed that the user mainly interfered with

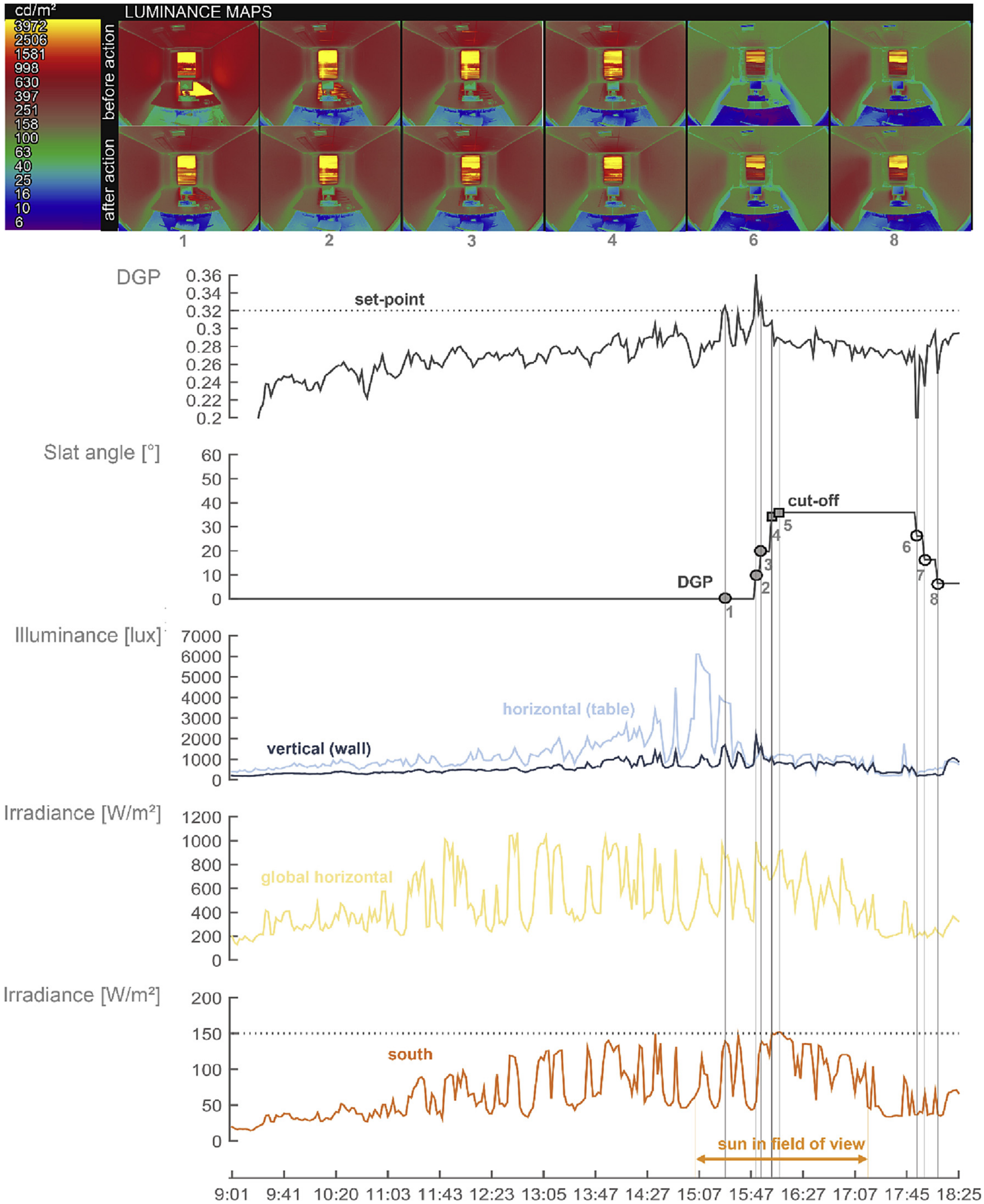

Fig. 10. The DGP control strategy is combined with the cut-off angle strategy to improve the visual comfort.

the controller system to gain more daylight in the interior environment. During periods of changing weather conditions the users accepted a range of glare up to a DGP of 0,35. The controller system reacts immediately to glaring conditions, even when the weather conditions are rapidly changing. Thus, a glare source (DGP higher than 0,30) that is only present for a couple of minutes already results in a closed blind. At this point, the blind is maintained completely closed for at least 20 min or maintained in an intermediate state for at least 10 min to avoid too much disturbance. The resulting reaction of the users was to open up the blind faster. The blind was already opened by the controller system to an intermediate state in 45% of the overruling opening actions and the DGP value was always lower than 0,28. This issue can be solved by letting the controller system first evaluate if the outside weather conditions are rapidly changing or stable. The controller system should only impose a change to the position of the blind if the latter is true, because the results of the questionnaire show that the users prefer a possible short exposure to visual hindrance over less daylight in the interior environment.

Blind 4 was operated the least. A possible reason is that the main influence of blind 4 on the interior environment is only noticeable for the users located at the desks in the row under blind 4. Whereas

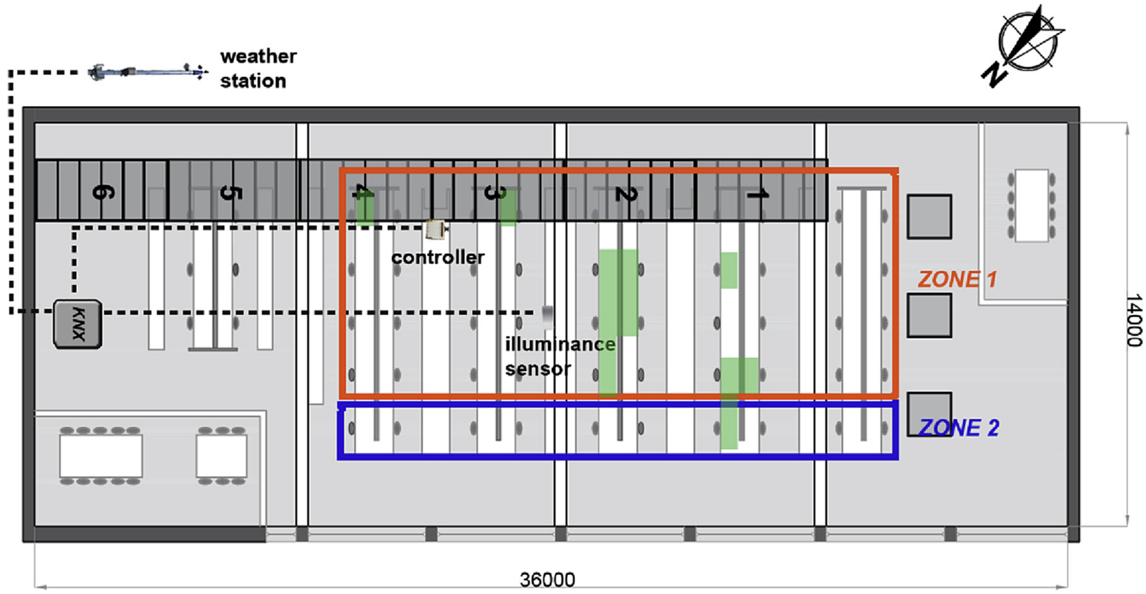

Fig. 11. Plan view of office space with indication of the 11 users that actuated the blinds (green coloured desks). Glare from the roof lights never occurs in zone 2 (zone in blue), for the other desks glare may occur (zone 1 in orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Number of actions to open or close a roller blind by the controller system and users, with the indicated answers on the questionnaire.

Action	Answer questionnaire	Blind 1	Blind 2	Blind 3	Blind 4
Open (user)	More light in the interior	10	7	8	2
	No answer (when opened)	1	1	3	–
Close (user)	Less glare	3	2	1	–
	Less light on the computer	4	2	–	–
	Less light in the interior	1	–	–	–
	No answer (when closed)	2	7	–	2
Open (controller)		–	–	165	–
Close (controller)		–	–	87	–

the position of blind 1,2 and 3 influences the visual comfort in at least two different rows of desks, thus they can influence the level of visual comfort for more users. Blind 4 remained open for 88% of the time. Blind 1 was operated 21 times, but remained closed for 67% of the time. Blind 3 was actively controlled by the controller system and this showed that the blind was only closed for 33% of measuring period (Fig. 12). This shows that the control strategy has a positive influence on the amount of daylight that enters room.

4. Conclusion

This paper describes the experimental measurements of a newly developed controller system and a control algorithm, which can control a shading device and avoid visual discomfort. The goal was to use a low-resolution camera to assess the DGP as a control parameter in order to avoid visual discomfort in an indoor office environment, without compromising the daylight availability.

The first tests in a mock-up office cell showed the potential of using a low-resolution camera with a miniature sensor as a picture sensor: the level of DGP was kept below the perceptible limit and at the same time enough daylight was provided in the room. Further testing with users investigated whether this strategy complies with the actual visual comfort a user perceives. Results showed that DGP underestimated the impact of direct sunlight in some cases. Hence, the set-point for glare was lowered by the users when direct sunlight was present. Still, an average horizontal illuminance of over

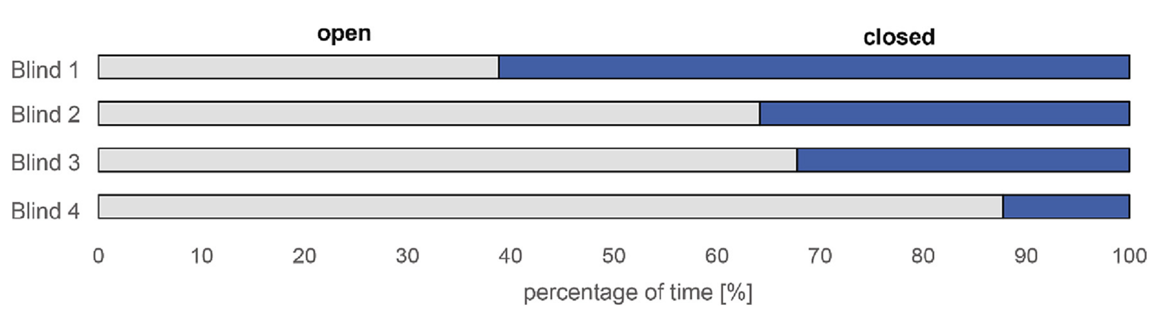

Fig. 12. The amount of time each roller blind remained opened or closed during the measurement period.

1300 lux on the table and an average vertical illuminance of 1200 lux in the immediate working area of the user was measured. The third scenario applied a combined control strategy of the DGP and the cut-off angle, which improved the visual comfort and still maintained enough daylight to create a comfortable working environment, with an average horizontal illuminance of 1500 lux. Thus, even though the low-resolution camera could underestimate glare sources in comparison to a high resolution camera, it is possible to use a low-resolution camera to minimize visual discomfort, especially in combination with a control system which can allow for users to overrule the actions.

Another challenge, was to show the applicability of the control strategy on other shading systems as well. The second case-study consisted of external roller blinds in a roof light. The limit for the DGP was set to a lower value. Results showed that visual discomfort was minimized, as only 1,8% of all user actions was imposed to override the controller system due to visual discomfort. However, the users overrode the controller system several times (20% of all actions) to increase the amount of daylight in the interior environment. Although, the automated roller blind was only closed completely for 33% of the time, which still allowed for natural daylight to enter the room. It is recommended to avoid immediate closing of the shading system, when glare occurs under rapidly changing weather conditions.

Further research and more extensive measurements are needed to verify the validity of these findings in a broader context, including different office types, with different shading systems and different positioning of the users and controller system. Also, performing numerical simulations can quantify the impact, not only on the visual but also, on the thermal comfort when using this control strategy compared to other existing strategies. In conclusion, the research shows a potential of using a low-resolution camera to evaluate the indoor visual comfort and a control strategy to enhance visual comfort as a user perceives it.

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